A Search for Radio Pulsars in Southern Supernova Remnants

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ABSTRACT

We have searched 40 southern Galactic supernova remnants for radio pulsars. Our survey covered each target remnant in its entirety and was, on average, sensitive to pulsars having luminosities greater than ~100 mJy kpc^2 at 400 MHz. In addition to eight rediscoveries of known pulsars, we have discovered two new pulsars, PSR J1104-6103 and PSR J1627-4845, although both have characteristic ages over two million years, and hence are not likely to be associated with their target remnants. However, the association of PSR J1627-4845 with its target remnant, G335.2+0.1, is plausible if the pulsar was born with a long spin period. The association requires further study before its veracity is determined. We conclude the main inhibiting factor against the discovery of new young pulsars is sensitivity, suggesting deeper searches of supernova remnants are warranted.

Subject headings: Pulsars: General - Pulsars: Individual: PSR J1104-6103, PSR J1627-4845 - supernova remnants

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1. Introduction

Some sixty years ago, it was proposed that neutron stars were born in supernova explosions (Baade & Zwicky 1934), yet the present understanding of the explosions and the remnants they leave behind remains incomplete. That supernova explosions and supernova remnants are associated is well-dc~tc!rI1lillc:cl because of historical records going back ~2000 yr, and the discovery of neutron stars' in the Crab and Vela supernova remnants established Baade & Zwicky's hypothesis as correct. However attempts at classification of different types of supernovae (Type Ia, Ib, Ic, II) and different types of remnants (shell, plerion, composite) (van den Bergh 1988), not to mention supernova progenitors and degenerate stellar remnants, has met only limited success. Helfand & Becker (1984) summarized the situation, and although some progress has occurred since then, the overall picture remains unchanged.

Pulsar-supernova associations are a potentially valuable tool for understanding the fate of massive stars and the birth and evolution of neutron stars and supernova remnants (SNRs) in the Galaxy. The establishment of a collapsed object as part of the SNR is key to hopes of classifying the remnant in terms of one type of explosion (in this case Type II or Type Ib, Ie.). Furthermore, pulsar associations provide independent estimates of crucial remnant properties of age and distance. Pulsars can also elucidate unusual morphology in a remnant, as in the proposed association between PSR B1757-24 and G5.4-1.2 (Frail & Kulkarni 1991; Manchester *et al.* 1991), where the morphology otl)c]-wise might lead to a misclassification (e.g. Becker & Helfand 1985).

In addition, there is independent strong motivation to search for young pulsars. With their higher spin-down luminosities, young pulsars are more likely to be detected at X-ray and γ-ray energies. In contrast to radio, high-energy emission comprises a significant fraction of the pulsar's energy budget, (e.g. Fierro *et al.* 1993), hence it may provide the most important observational diagnostic for the yet mysterious rotation-powered neutron star energetics. Furthermore, young pulsars preferentially exhibit glitch behavior (e.g. McKenna & Lyne 1990; Kaspi *et al.* 1993), useful as a diagnostic of the physics of neutron star interiors. Finally, young pulsars typically show both interesting random rotational irregularities (e.g. Johnston *et (11.* 199JIJ), and their rapid spin-down often allows the measurement of deterministic rotational properties that constrain electromagnetic braking (e.g. Lyne, Pritchard & Smith 1988; Kaspi *et al.* 1994).

Three previous searches of comparable sensitivity looking for pulsars in SNRs have been published. Manchester, D'Amico & Tuohy (1985), who searched a total of 53 Galactic remnants at 1420 MHz, found four new pulsars. Recently Gorham *et al.* (1995) reported on their search of 18 SNRs using the Arecibo radio telescope at 430 and 1420 MHz, and Biggs & Lyne (1995) reported on their search of 29 SNRs using the Lovell telescope at Jodrell

Bank over a similar frequency range. Neither of these recent scare.llcs resulted in any new detections. One major weakness of all these surveys was that the telescope beam sometimes encompassed only a small fraction of the target SNR. Since many recently proposed pulsar/SNR associations involve a pulsar that is not at the center of the remnant or is even outside the remnant bou ndaries (Manchester *et al.* 1991; Frail & Kulkarni 1991; Frail, Kulkarni & Vasisht 1993; Caraveo 1993), previous searches may have missed pulsars. Untargeted searches have discovered young pulsars which have subsequently been proposed for associations with nearby remnants (e.g. Jol mston *et al.* 1992).

Here we report on a search carried out at 430, 660, and 1520 MHz toward 40 Galactic southern SN Rs. In this search we have ensured complete coverage of every target, either by verifying that the telescope beam encompassed the entire remnant, or by using multiple pointings with slight offsets toward a target when necessary. We have discovered two previously unknown pulsars, PSR .11104- 6103 and PSR J1627- -4845. In § 2 we describe our observations and data analysis, in § 3 we present our results, including a list of previously known pulsars rediscovered during our search. In § 4 we present timing observations of the! two new pulsars discovered as part of this effort, PSR J 1104- 6103 and PSR J 1627-4845. In § 5, we discuss our results, and consider the plausibility of the associations between the two new pulsars and their target remnants.

2. Observations and Analysis

The observations were made with the 64-m radio telescope at Parkes, NSW, at various epochs between 1988 July and 1989 January, and additionally over five days in 1992 July. Cryogenically-cooled systems receiving orthogonal linear polarizations were used at all three observing frequencies, 436, 660, and 1520 MHz. The signals were down-converted to an intermediate frequency, filtered in multi-channel filter-banks, detected, and band-limited. The filter-banks consist of 2 x 256 x 125 kHz filters at 436 MHz, 2 x 128 x 250 kHz filters at 660 MHz, and at 1520 MHz, 2 x 64 x 5 MHz filters. After summing the polarizations, the signals were sampled using one-bit digit ization and recorded on magnetic tape. The sample interval was 1.2 ms at all three frequencies for the 1992 observations, as well as for the earlier observations at 1520 MHz. At 660 MHz, the sample interval was 0.3 ms for the earlier observations, however in subsequent processing, every th ree adjacent sa mples were summed, for an effect ive sample interval of 0.9 ms, to reduce t he volu ne of data. Sy stem temperatures for the 436, 660, and 1 520 MH z systems were 55, 45, and 50 K respectively, and the cfkw.five half-power beam widths at Parkes are 38', 27', and 11' respectively.

Off-line, Fast Fourier transforms were performed on the data sets at a variety of different dispersion measure (DM) values. At 430 MHz, 160 loops in the range 0–400 pc cm^{-3} were performed, while at 660 MHz, 80 loops for a DM range of 0–550 pc cm^{-3}, and at 1520 MHz, 70 DM loops ranging from 0–2200 pc cm^{-3}. Smaller DM ranges were used at the lower radio frequencies because the effects of interstellar scattering at high DM make the detection of pulsars more difficult. All processing was done on the Convex 220 computer at the ATNF. The size of the transform was chosen to be close to the total number of samples in an observation, with zero padding for transform sizes exceeding the data length. Each spectrum was searched for pulsar-like signals, and sensitivity to short duty cycle signals was improved by incoherently summing 2, 4, 8, and 16 harmonics of the fundamental. Periodicities having signal-to-noise ratios greater than eight and not observed in more than one direction (i.e. not obviously terrestrial interference) were subject to further analysis. Typically, at least three candidates per observation made this cut. The data were then folded at a variety of periods and DM's near the optimal values determined by the Fourier transform software, and the period and DM corresponding to the highest signal-to-noise pulse profile were recorded. The profiles, as well as their temporal and frequency behavior, were then inspected visually, with top candidates noted for subsequent attempted confirmation. Typically fewer than one in 25 of the candidates had sufficient signal-to-noise ratio and pulsar-like qualities for a reobservation of the target.

A list of our target remnants is presented in Table 1. Targets were generally chosen on the basis of their southern location and inaccessibility from northern sites, although during gaps in the schedule more northern sources were observed. In addition, we searched only remnants for which no association with a young pulsar at the time of observation was proposed, and tended to prefer remnants with higher surface brightness (as many proposed associations involve bright remnants) but included low-flux-density remnants during gaps in the schedule. In the Table, the attributes of each remnant are in general as listed in the Green (1988) SNR catalog, as revised in the online WWW version at URL `http://www.phy.cam.ac.uk/www/research/ra/SNRs/snrs.data.html`. The remnant types are abbreviated as S for a shell remnant, P for a plerion, C for composites, and C? for objects difficult to classify. Note the revision of the type of G11.2–0.3 from shell, as listed in the catalog, to composite, after the work of Vasisht *et al.* (1995). The remnant sizes given are diameters, with major and minor axes of non-circular remnants given where appropriate. The fluxes are at 1 GHz, and the coordinates are of the approximate remnant centers. The estimated distances to each target, listed in column 6 of the Table, were obtained from the numerous well-organized references in the Green catalog; remnant distances are notoriously difficult to measure, and we have made every attempt to adopt the most recent or, what we consider the most reliable, estimate available in the literature. In cases where no estimate was available, or where only upper limits or extremely unreliable estimates have been published, we have adopted a distance based on the highly uncertain $\Sigma - D$ relation (Clark & Caswell 1976) as a last resort. Although the distance estimates are to be regarded as approximate, in adopting distances from a wide variety of sources and estimation techniques, we hoped to minimize systematic errors in the subsequent analysis (See § 5 below).

Observations were made at three different radio frequencies depending on scheduling constraints, with some targets observed at several frequencies, some observed at a single frequency multiple times, and some observed only once. However in spite of scheduling constraints, we ensured that the entirety of the remnant was covered by at least one observation, either by choosing the lowest observing frequency to maximize the telescope beam size or by doing a number of pointings at slightly different positions. Columns 2, 3, and 4 in Table 2 summarize our observations at each observing frequency. The areas of sky surveyed were 5.7 square degrees at 430 MHz, 4.9 square degrees at 660 MHz, and 0.77 square degrees at 1520 MHz. Accounting for overlaps, a total of 8.5 square degrees were surveyed at one or more of the three frequencies.

To establish our survey's sensitivity, we estimated the minimum detectable flux density for each source at each observing frequency using the formula

$$S_{\rm min} = S/N_{\rm min} \times F \times \sqrt{D} \times \sigma, \tag{1}$$

where $S/N_{\rm min} = 8$ for the minimum interesting pulse signal-to-noise ratio, $F = 1.21$ to account for the loss due to one-bit digitization, D is the pulsar duty cycle, taken to be 5%, and σ is the rms noise, estimated using the expression

$$\sigma = \frac{(T_{\rm sys} + T_{\rm sky})/G + S_{\rm SNR}}{\sqrt{2BT}}. \tag{2}$$

In the above, $T_{\rm sys}$ is the system temperature in K, $T_{\rm sky}$ is the sky temperature at the remnant coordinates in K, evaluated using the Haslam *et al.* (1982) 408 MHz map, scaled to the appropriate observing frequency assuming a -2.8 spectral index, $G = 0.000625$ K mJy^{-1} is the Parkes telescope gain, B is the observing bandwidth, T is the integration time, and $S_{\rm SNR}$ is the remnant flux density in mJy. $S_{\rm SNR}$ was evaluated using the fluxes listed in column 5 of Table 1, and assuming a spectral index of -0.5 for shell sources, 0 for plerions, and -0.25 for composite or unclassified remnants. For remnants larger than the beam, this is an overestimate, which results in a conservative $S_{\rm min}$. The lowest values of $S_{\rm min}$ for each observing frequency are tabulated in columns 5, 6, and 7 in Table 2. The final column in the Table shows the lowest of the three when extrapolated to 400 MHz, assuming a typical pulsar spectral index of -2, unless the lowest was from an observation that did not cover the remnant in its entirety (2 cases), or for which scattering and/or dispersion was likely to reduce the sensitivity significantly (4 cases). In the former case, $S_{\rm min}$ was chosen from an observation at a frequency for which the telescope beam was sufficiently large. In the latter case, we chose S_{min} from that of a higher observing frequency for which the effects of dispersion and scattering are expected to be minimal, if possible. Sources for which this was not possible are indicated by asterisks in the '1'able. Dispersion and scattering are discussed in more detail in § 5.5 Mow.

We caution that the values for S_{min} correspond to the nominal telescope beam center; the sensitivity is reduced for sources away from the center. However, in all cases we have ensured that! the entire remnant was within the half-power beam, hence the minimum detectable fluxes for sources on remnant perimeters are increased in all cases by less than a factor of two, and, in fact, there is still significant sensitivity to pulsars well outside most remnant boundaries. The sensitivity may also be reduced because of a number of effects which broaden the intrinsic pulse width W and correspondingly increase the duty cycle, particularly for snort periods P. The broadening arises from the finite sample interval τ_i, dispersion across the finite frequency channel width b, and multipath interstellar scattering, characterized by scattering time τ_s. Although not all the relevant pulse broadening parameters are known, we provide the appropriate expression for the observed duty cycle D_o for use in evaluating the minimum sensitivity (Eq. 1) for specific parameters:

$$D_o = \frac{W_o}{P - W_o}, \tag{3}$$

where the observed pulse width W_o is given by

$$W_o = \left(W^2 + \tau_s^2 + \tau_i^2 + \left(\frac{204}{f}\right)^6 \mathrm{DM}^2\, b^2\right)^{1/2}, \tag{4}$$

where f is the observing frequency and b is the channel bandwidth, both in MHz, and all time scales, W_o, W, τ_i and τ_s are in ms.

3. Results

We have discovered two new pulsars in this survey, 1'S1/.11104 --6103 and 1'S1{J1627- 4845. In addition, eight previously known pulsars were rediscovered and are listed in Table 3. In general, the discovery signal-to-noise ratios are consistent with our estimates of this search's sensitivity, given the pulsar's flux density and its offset from the beam center, accounting for scintillation, and uncertainties in the pulsar spectral indexes and remnant fluxes. All known pulsars detected in this search have either been considered for SNR associations before (see footnotes to Table 3), or have characteristic ages greater than 50 0,000 yr, suggesting that they are not associated with the presumably much younger target remnant (however see § 5.7.2 below).

4. Timing Observations of PSR J1104−6103 and PSR J1627−4845

Timing observations were made using the same observing system described in § 2. Off-line, the data were folded at a variety of periods and DMs around the nominal values and the resultant profiles with the highest signal-to-noise ratio saved. They were then convolved with high signal-to-noise ratio templates (see Figs. 1 and 2). Arrival times were recorded, and the standard TEMPO pulsar timing software (Taylor & Weisberg 1989) was used for the subsequent analysis, as was the JPL DE200 planetary ephemeris.

PSR J1104−6103 was detected in 1520 MHz data obtained for the Galactic supernova remnant G290.8−0.1. Following its discovery, a total of 37 timing observations were obtained between 1992 July and 1994 July, with 31 observations at 1520 MHz and seven at 430 MHz. Typical lengths of observations for this pulsar were 30 mins, which yielded average profile signal-to-noise ratios of $\sim$20 and pulse time-of-arrival uncertainties typically of $\sim$0.5 ms. The timing data are well-fit by a simple timing model for an isolated pulsar, with timing residuals dominated by measurement uncertainties and no evidence for any random rotational irregularities often referred to as "timing noise." Astrometric, spin and radio parameters for PSR J1104−6103 are provided in Table 4, in which numbers in brackets represent 1σ uncertainties. Figure 1 shows average pulse profiles at 430 and 1520 MHz.

PSR J1627−4845 was detected at 660 MHz while observing the remnant G335.2+0.1. After its discovery, 27 timing observations were made from 1992 August through 1994 July at 1520 MHz. Typical integration times were 30 min, and the signal-to-noise ratios of average profiles were typically $\sim$8, which resulted in timing uncertainties of $\sim$4 ms. The timing data for PSR J1627−4845 are also well-fit by a simple timing model for an isolated pulsar, although its timing residuals are not completely consistent with the measurement uncertainties, suggesting the presence of a small amount of timing noise. Astrometric, spin and radio parameters for PSR J1627−4845 are provided in Table 4. Figure 2 shows the average pulse profiles at 1520 MHz and 660 MHz. The 660 MHz profile shown is its discovery observation; because of the obvious scatter-broadening which gives rise to large errors in arrival times, this pulsar was not subsequently observed at this frequency.

5. Discussion

In summary, we have searched 40 remnants, and detected pulsars ten times, seven of which were within the half-power beam, two of which were discoveries of previously unknown sources. In this section we discuss whether either of the two new pulsars is associated with its target SNR. First, we estimate the number of new associations we expected to find in this survey, considering reasons why pulsations might not have been detected from every target. We show the number is ~2, although this may be an overestimate. Next, we estimate the number of expected detections, within the Half-power beam, of field pulsars unassociated with Large.ts, and show it is ~5. On statistical grounds, there is therefore no need for any detected pulsar to be associated with its target. Detailed modeling of many of the issues disc ussed below has been done by Gaensler & Johnston (1996), yielding similar conclusions. Finally, we consider the details of the possible associations involving the two new pulsars, and demonstrate that PSR J] 104- 6103 is unlikely to be associated with its target, while the association between PSR J 1627−4845 and G335.2+0.1, though most likely due to chance superposition, is tentatively plausible under the assumption that pulsars can be born with long spin periods.

5.1. The remnant is not a result of a neutron-star-creating supernova

Observational evidence shows that the majority, ~85% of supernovae are of Type Ibc and Type II (Evans, van den Bergh & McClure 1989; Muller *et al.* 1992), which are commonly thought to have evolved from massive progenitors, and hence are likely to have formed compact objects. This is consistent with the rough agreement between the rate of supernovae (and birth rate of remnants) with the estimated neutron star birth rate (Helfand & Becker 1 984; Weiler & Sramek 1988). It is true, however, that the neutron star birth rate is debated (Narayan & Ostriker 1990; Lorimer *et al.* I 993), and the fraction of Type Ibc and II supernovae that produce neutron stars, as opposed to black holes (e.g. Bethe & Brown 1995) is as yet controversial (although there is reason to believe black-hole-creating supernovae leave behind no traditional remnants). Nevertheless, requiring only a small fraction of supernovae to produce neutron-star remnants would be difficult to reconcile with the majority of the evidence. Furthermore, there exist numerous point sources discovered in other regions of the electromagnetic spectrum (e.g. Becker, Helfand & Szymkowiak 1982; Petre, Becker & Winkler 1995) which have been proposed as candidates for neutron stars in SNRs, as well as plerion synchrotron nebulae that quite plausibly contain pulsars (Seward & Wang 1 988), regardless of whether radio pulsations are ever detected.

5.2. The remnant contains a neutron star emitting little or no radio emission

To address whether our results can be explained by very weak (or effectively no) radio emission, we consider our survey's sensitivity in more det ail. Using the S_{min} values in Table 2 together with the remnant distance estimates d provided in Table 1, we have computed upper limits to the 400 MHz luminosities of any pulsars associated with each of the targets as $S_{min}d^2$. Although these upper limits depend strongly on the distance estimates which have large uncertainties, we assume that there are no major systematic biases, because the distance estimates are from a variety of different measurement techniques. Luminosity upper limits obtained in this way ranged from 5 mJy kpc^2 to 500 mJy kpc^2 and have mean $\langle L_{upper} \rangle$ -100 mJy kpc^2. Thus, this survey represents nearly an order of magnitude sensitivity improvement over the Manchester, D'Amico & Tuohy (1985) survey.

Figure 3 shows histograms of luminosities of all pulsars in the Taylor, Manchester & Lyne (1993) catalog for which luminosities are available (striped region), as well as the mean luminosity upper limit $\langle L_{upper} \rangle$ for this survey (vertical line). Some 60% of known pulsars have luminosities greater than $\langle L_{upper} \rangle$. However, the known pulsars represent only a fraction of the Galactic pulsar population, and are very likely to be overrepresentative of the brightest members. We use the work of Lorimer *et* al. (1993) to correct for this problem. With their model (see their Figure 7), >89% of all pulsars have luminosities below 100 mJy kpc^2, the lower limit a result of the poor statistics on pulsars having luminosities less than 10 mJy kpc^2. Since very little statistical information is available on pulsars having L < 10 mJy kpc^2, we hesitantly assume we were sensitive to 11% of all pulsars in this survey, although a large population of very low-luminosity pulsars would require a significant modification of this number. Indeed Gaensler & Johnston (1996) have done careful simulations of the time evolution of both pulsars and SNRs, as well as of the selection effects involved in the detection of each class of object, and have shown that, because of luminosity alone, most shell SNRs will not have a detectable pulsar associated with them.

We note that the Lorimer *et al.* (1993) luminosity law suggests younger pulsars have higher luminosities than the general population) although less so than previous studies have suggested (e. g. Emmering & Chevalier 1989). In Figure 3, we have also shown the luminosities of the 21 known pulsars having characteristic ages less than 100,000" yr (crossed region). Their distribution is not obviously unlike that of the general population. We therefore choose not to assume young pulsars have higher luminosities, in spite of conventional wisdom. Furthermore, it has been speculated that some pulsars might not turn on until significantly after their births, due, for example, to initial magnetic field growth} (Radhakrishnan & Srinivasan 1980). However in the absence of detailed models or corroborative observation evidence, we do not consider this possibility here.

5.3. The remnant contains a radio pulsar which is not beaming toward us

The discovery of the rotation-powered high-energy pulsar Geminga (Halpern & Holt 1992) underlined the fact that not all pulsars have radio beams directed toward us. The beaming fraction of pulsars is not easy to determine, but attempts have been made using two methods. The first is by interpreting total intensity and polarization of pulse profiles in terms of a geometric model for the emission beam (e.g. Radhakrishnan & Cooke 1969), and noting some dependence of the beamwidth on rotation period. The exact form of the dependence is disputed (Narayan & Vivekanand 1983; Lyne & Manchester 1988; Biggs 1990) however it is generally agreed that the beaming fraction for young pulsars is between 0.3 and 1.0. The second method for determining the beaming fraction, only applicable to young pulsars, is in fact by considering the known pulsar/SNR associations, and noting that the vast majority of the youngest known pulsars are in fact found in SNRs (Narayan & Schaudt 1988), implying a high beaming fraction, close to 1.0. Frail & Moffett (1993), however, after deep VLA imaging of seven plerion or composite remnants, assumed to contain active pulsars, concluded the beaming fraction was closer to 0.6 after finding no new pulsars.

5.4. The pulsar has escaped the remnant boundaries

One alternative to relying on luminosity or beaming arguments to explain the paucity of new associations is to note that Lyne & Lorimer (1994) have shown the mean pulsar birth velocity, a result of an asymmetric supernova explosion giving the pulsar a velocity "kick," is considerably higher than previously thought, near 450 km s^{-1}. Indeed there exists a number of proposed associations between pulsars and SNRs, in which the pulsar is found near or well outside the remnant boundaries (Manchester *et al.* 1991; Frail & Kulkarni 1991; Frail, Kulkarni & Vasisht 1993; Caraveo 1993), although they may also represent accidental superpositions in regions where pulsars and SNRs are numerous (e. g. Kaspi *et al.* 1993; Johnston *et al.* 1995b). No independent confirmation, such as measurements of timing or VLBI proper motions, of the implied large velocities in any of the proposed associations has yet been made.

To estimate the fraction of pulsars that have left the remnant boundaries, we first estimated remnant ages using the expression for Sedov expansion derived by Clark & Caswell (1976), $D = 0.93\,t^{0.4}$ for D, the remnant diameter, in pc, and t, the remnant age, in yr. D was estimated from the angular size, and the distance estimate, both tabulated in Table 1. We assumed the Lyne & Lorimer (1994) mean pulsar transverse velocity at birth of 345 km s^{-1}. Next we calculated the parameter $\beta = \theta_{PSR}/\theta_{SNR}$ (Shull, Fesen & Saken 1989), where θ_{PSR} is the angular offset of the pulsar from the remnant center assuming it was born there, and

$\theta_{\rm SNR}$ is the mean angular radius of the remnant. A value of $\beta > 1$ thus indicates the pulsar is outside a circular remnant. We estimated β only for shell remnants, under the standard assumption that plerions and composite remnants contain an active pulsar (Seward & Wang 1988; Frail & Moffett 1993), and obtain a mean value $\langle\beta\rangle \sim 0.16$. Assuming a Maxwellian velocity distribution, this implies that all pulsars lie within the target remnant boundaries. Even if the estimated ages are significantly underestimated, for example if expansion slowed because of a dense medium, or if many of the remnants are in the later radiative-cooling phase, this result holds.

Gaensler & Johnston (1995b ,c), in combination with existing models for pulsar and SNR evolution and detection selection effects, Il ave carried out a detailed simulation of a Galactic population of SNRs and pulsars, comparing their results with the known associations, and estimating the number of pulsars expected to be found inside remnants. They find that the expected number of true associations for which $\beta > 1$ is only $\sim$5% for a remnant population) having ages evenly distributed below 60 kyr, rising only to $\sim$30% for a similar population with maximum age 200 kyr. The mean age of the remnants in our survey is well under 60 kyr; thus our rough estimate that any neutron star associated with a target remnant lies within the remnant boundary is consistent with their independent result.

5.5. Scattering and 1)ispersion

Dispersion and scattering result in a relatively small reduction in our sensitivity, primarily because 3/4 of all targets were observed at 1520 M 11 z, where the effects are practically negligible. Care must be taken since not all 1520 MHz observations covered the targets in their entirety (in those cases, a lower frequency did), and also,]/4 Of our targets were only observed at lower frequencies, where scattering and dispersion may be important. Generally, the most distant SNRs, likely to house the most scattered pulsars, tend to have smaller angular diameters, and hence were most likely to have been covered by the high frequency beam. '1'0 quantify the impact propagation effects may have had, we used the distance estimates in Table 1, together with the Taylor & Cordes (1993) model to estimate the DM and scattering toward each remnant. We caution that this method, given the large uncertainties in the distances, as well as in the Taylor & Cordes (1 993) model, is approximate at best. For 24 of the 40 targets, observations at 430 MHz are predicted in this way to have resulted in DM smearing of $\lesssim$ 4 ms, and scattering of $\tau_s \lesssim 13$ ms. For six of the remaining 16, observations at 660 MHz are predicted to have resulted in similar effects. Of the remaining ten, seven were observed and covered completely at 1520 MI I z, where the predicted effects of scattering and dispersion are small. Thus, 01113'111 ree Of the targets are very likely to have suffered strongly deleterious effects - they are G21.8−0.6, G328.4+0.2, and G335.2+0.1. The values for S_{min} in Table 2 reflect appropriate minimum flux values (i.e. at a frequency at which the entire remnant was covered and for which scattering and dispersion are unlikely to play a major role) except for the above three targets, which are noted by asterisks in the Table.

We caution that these effects are greatly exacerbated for short period pulsars. If, in spite of the fact that the mean period of known pulsars having characteristic age less than 100,000 yr is 280 ms, most SNR pulsars have periods comparable to or shorter than that of the Crab pulsar, we will have significantly underestimated the problem. Indeed, that the mean period of young pulsars is not smaller may well be a result of precisely these effects. Furthermore, if SNRs themselves contribute significantly over and above the Galactic scattering and dispersion which were modeled by Taylor & Cordes (1993), we will have similarly underestimated the sensitivity loss. Finally, some pulsars might be unobservable due to obscuration by a binary companion wind (e.g. Johnston *et al.* 1995a), although dynamical considerations suggest most binaries are disrupted by high birth velocities. Uncertainties in mass-loss rates of potential companions (e.g. Kaspi, Tauris & Manchester 1996) render estimation of this effect difficult.

5.6. Summary

In summary, it is clear there are many uncertain parameters that determine the success of this, and other searches for pulsars in SNRs. We construct here an approximate formula for use in estimating the number of young pulsars associated with target remnants, N, that might be expected to be detected in this and other similar surveys:

$$N = f_{\rm SNR} \times f_{\rm L} \times f_{\rm b} \times f_{\rm ISM} \times (N_{\rm P,C} + f_{\beta} \times N_{\rm S}), \qquad (5)$$

where $f_{\rm SNR}$ is the fraction of all supernovae that produce neutron stars, $f_{\rm L}$ is the fraction of all neutron stars with detectable radio emission, $f_{\rm b}$ is the fraction of all radio emitters that beam toward the Earth, $f_{\rm ISM}$ is the fraction of pulsars detectable in spite of dispersion and scattering in the interstellar medium, $N_{\rm P,C}$ is the number of plerion or composite remnants, f_{β} is the number of pulsars inside the parent shell remnant, and $N_{\rm S}$ is the number of shell remnants. According to the above discussions, we estimate $f_{\rm SNR} \sim 0.85$, $f_{\rm L} \sim 0.11$, and $f_{\rm b} \sim 0.6$. Although our estimates suggest $f_{\rm ISM} \sim 0.925$, we conservatively double the estimated scattering and dispersion effect because of the large uncertainties, and adopt $f_{\rm ISM} \simeq 0.85$. Finally, $f_{\beta} \sim 1.0$, and for this survey, $N_{\rm P,C} = 13$ and $N_{\rm S} = 27$. Thus, with these estimates, we find that we should have detected $\sim$2 new young pulsars.

However we note that because we searched only remnants in which no association has beensuggested, 0111" sample of SNRs is biased. Had we included some remnants for which associations with young pulsars have been proposed, the predicted number of detections, ~2, would not have changed significantly. However, given our typical search parameters, we would have detected significantly more pulsars. For example, wc would have easily detected the Vela pulsar searching the Vela remnant. We would have detected PSR B1853+01, near W44, at any observing frequency for typical search parameters, as Well as PSR 111757-24 near G5.4-1.2. '1'1111s, had our sample of SNRs been complete and included just two remnants for which associations already mist, those associated pulsars would have comprised the two expected to be detected. Hence, we cannot unambiguously assert this survey should have discovered even a single new pulsar associated with a remnant.

Gaensler & Johnston (19951J) have argued that many apparent associations between old pulsars and SNRs are purely geometric in nature. Therefore we must also estimate the number of pulsars unassociated with target remnants we should have found, from the areas of sky surveyed in this scare.1], and estimates of the space densities of the general pulsar population. At 1520 MHz, wc searched 0,77 square degrees, concentrated largely in the Galactic plane, to an average limiting flux density of 0.17 mJy. Johnston *et al.* (1992) surveyed the southern Galactic plane in the region $270° \leq l \leq 20°$ and $|b| < 4°$ to a limiting flux density of 1 mJy, and detected 100 pulsars. Using the implied surface density, and assuming the number of detectable pulsars is proportional to $S_{\rm min}^{-3/2}$, wc estimate we were likely to have detected ~1.2 pulsars at 1520 MHz. Similarly, at 430 MHz, from the distribution of pulsars detected in the recent Parkes all-sky survey (Manchester *et al.* 1996), their limiting sensitivity, our search area of 5.7 square degrees, and our average $S_{\rm min}$ at 430 MHz of 1.9 mJy, we estimate we were. likely to have detected ~2 pulsars. The number expected to have been detected at 660 MHz is harder to estimate since there have not been systematic searches at this frequency, however it is likely to be approximately the same, given that we surveyed a comparable area to an average limiting flux density of 1.() mJy, and that the typical pulsar spectra] index is - 2. Thus, we expect to have deteced ~5 pulsars by chance. From Table 3, we see we detected seven pulsars within, and three bright sources well outside, the half power beam. Thus, the probability of having detected new pulsars unassociated with target SNRs is sizable, and statistically, no pulsar detected in this survey need be associated with its target SNR.

5.7. Is either PSR J1104–6103 or PSR J1627–4845 associated with its target remnant?

5.7.1. PSR J1104–6103 and G290–0.1

We do not consider an association between PSR J1104-6103 and G290.8–0.1 likely for several reasons. First, the Taylor & Cordes (1993) pulsar distance model suggests that for DM = 78 pc cm^{-3}, this pulsar lies at a distance of 2.3 kpc, with an uncertainty of ~25%. By contrast, HI absorption measurements by Radhakrishnan *et al.* (1972) imply the remnant's distance is >3.4 kpc, and Clark & Caswell (1976) put it at ~6 kpc via the $\Sigma - D$ relation. Furthermore, the pulsar's position lies well outside the remnant, and there is no morphological evidence for any association. In addition, the pulsar's characteristic age of $\tau = 2.3 \times 10^6$ yr is far larger than the expected lifetime of an SNR, rendering an association implausible unless spin-down ages are significant overestimates of true pulsar ages (however see § 5.7.2). Finally, we note that a new short-period pulsar, PSR J1105–6107, was recently discovered near the SNR G290.8–0.1 (Kaspi, Manchester & D'Amico 1996)[6] and the association between the two is more plausible than that discussed here.

5.7.2. PSR J1627–4845 and G335.2+0.1

PSR J1627–4845's timing position lies well inside the boundaries of the target SNR G335.2+0.1, offset from the nominal remnant center by ~4′, implying *beta* ~ 0.4, as shown in Figure 4. The distance to the pulsar, from the Taylor & Cordes (1993) distance model, is 6.8 kpc, with uncertainty ~25%. The distance to the remnant has been estimated, using the admittedly uncertain $\Sigma - D$ relation, to be ~6.5 kpc (Clark & Caswell 1976). Thus, the position and distance of this new pulsar suggest an association is plausible. However, the pulsar, having characteristic age $\tau = 2.7 \times 10^6$ yr, is much older than the maximum age beyond which most SNRs are commonly assumed observable. This suggests the apparent superposition of the pulsar on the SNR is merely due to chance alignment.

Alternatively, we note that τ, estimated as $\tau = P/2\dot{P}$, is only an upper limit to the true pulsar age. In general, the true age is given by

$$\tau_{\rm true} = \frac{P}{(n-1)\dot{P}} \left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right], \tag{6}$$

[6] The timing position for PSR J1105–6107, as measured by Kaspi *et al.* (1996), lies well outside the remnant, as well as outside the 1520 MHz Parkes beam for all pointings toward this remnant reported in this search, which explains why it was not discovered as part of the presently described effort.

where n is the braking index and P_0 the spin period at birth, and where the pulsar magnetic field is assumed constant. Thus τ is a good approximation to τ_{true} only if $P >> P_0$ and $n = 3$. If the present spin period of PSR J1627-4845 is very close to the birth spin period, the pulsar is much younger than τ suggests, and an association with the remnant is plausible. There is some evidence that SNRs are observable up to ages of 100,000 yr Gaensler & Johnston (1995b). If, for PSR J1627-4845, $\tau_{true} = 100{,}000$ yr, then $P_0 = 600$ ms for $n = 3$. In this case, the pulsar's transverse velocity must be $\sim$70 km s^{-1} for it to have reached its present location $\sim 4'$ from the remnant center,[7] its assumed birth location. This velocity is somewhat lower than the mean pulsar birth velocity (Lyne & Lorimer 1994), but easily consistent with being part of the low end of the distribution. If PSR J1627-4845 is younger than τ suggests, it is difficult to reconcile its large P_0 with the short birth spin periods of many well-established young pulsars, unless "injection" of slowly-rotating neutron stars into the population occurs, as has long been suggested by various population synthesis studies (Vivekanand & Narayan 1981; Narayan 1987; Narayan & Ostriker 1990). The establishment of a firm association between a pulsar with a large characteristic age and an observable supernova remnant, for example, between PSR J1627-4845 and G335.2+0.1, would provide unambiguous evidence for the injection hypothesis. Measurements of 21 cm HI absorption in the radiation from G335.2+0.1 and PSR J1627-4845, to establish distances of both sources, as well as additional timing observations of the pulsar to look for timing noise or glitches, will clearly be of value in further assessing this possible association.

6. *Conclusions*

We have searched 40 southern Galactic supernova remnants for radio pulsars. Using our best flux limits together with distance estimates for each target, we find that on average, we were sensitive to pulsars having luminosities greater than $\sim$100 mJy kpc^2. Our survey covered each target remnant in its entirety, and though our sensitivity was reduced by up to a factor of two near remnant boundaries, there was significant sensitivity well outside many remnants, as evidenced by the discovery of PSR J1104-6103. Using reasonable assumptions about young pulsar luminosities, beaming fractions, velocities, radio propagation parameters, remnant ages, and the number of remnants that are the result of neutron-star-creating supernova, we estimate we should have detected $\sim$2 new young pulsars associated with their target remnants, although we note that our SNR sample is incomplete since it includes remnants for which associations have previously been proposed. We also estimate we should

[7]Here we take the remnant centre to be at approximately $\alpha(2000) 16^h27^m33^s$, $\delta(2000)$ - 484445, from Figure 4. We note that the remnant center as listed in Green's catalog (see Table 1) is offset by $\sim 2'$.

have detected ~5 pulsars unassociated with remnants by chance, assuming we were sensitive strictly within the half-power beam. We detected ten pulsars, including seven within the half-power beam, of which two were! not previous] y known. 1 lowever, both have characteristic ages of more than two million years, suggesting neither is associated with its target remnant. The association of one of those pulsars, PSR J 1627-4845, with its target, remnant G335.2+0.1, is plausible only under the assumption that some pulsars are injected into the population with long spin periods, as has been suggested by various population synthesis models (Vivekanand & Narayan 1981; Narayan 1987; Narayan & Ostriker 1990). The association requires further study before its veracity is determined.

If the association is shown to be false, this search will have resulted in no new pulsar/SNR associations, in spite of considerable observational e ffort. The largest factor inhibiting the detection of pulsars in our survey was sensitivity; this suggests deeper surveys of remnants are warranted , Alternatively, if in spite of our rough estimates, as well as those independently made by Gaensler & Johnston (1 996), many pulsars are found outside remnant boundaries because of kick velocities introduced at the supernova explosion, co]rsiderable reward might be wrought for the extra effort required to search exhaustively not Only remnant interiors, but also remnant surroundings.

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Table 1: Properties of target remnants (from Green's catalog and references therein).

Galactic Coordinates	Name	Type	Size (')	S (Jy)	d (kpc)	α (B1950) h	m	s	δ (B1950) d	'
G4.5+6.8	Kepler, SN 1604, 3C358	S	3	19	4.4	17	27	42	-21	27
G11.2-0.3		C[b]	8	6	5	18	08	30	-19	26
G18.9-1.1		C?	33	37	2	18	27	00	-13	00
G20.2-0.2		}}	10	10	5.4	18	25	20	-11	37
G21.5-0.9		P	1.2	6	5.5	18	40	37	-10	37
G21.8-0.6	Kes 69	s	20	69	10[a]	18	30	00	-10	10
G23.3-0.3	W41	s	27	70	4[a]	18	32	00	-08	50
G24.7+0.6		C?	30X15	20	5	18	31	30	-07	07
G27.8+0.6		P	50X30	30	2	18	37	06	-04	28
G29.7-0.3	Kes 75	C?	3	10	15	18	43	48	-03	03
G189.1+3.0	IC443, 3C157	s	45	160	1.5	06	14	00	+22	34
G260.4-3.4	Puppis A, MSH 08-44	s	60X50	130	3	08	20	30	-42	50
G279.0+1.1		s	95	30?	3	09	56	00	-53	00
G290.1-0.8	MSH 11-61A	s	15×10	42	6[a]	11	01	00	-60	40
G291.0-0.1	MSH 11-62	P	10	16	3.5	11	09	45	-60	22
G292.0+1.8	MSH 11-54	C?	12X8	15	3.6	11	22	20	-59	00
G296.1-0.5		s	33?	8?	7.7	11	48	40	-62	17
G296.5+10.0	PKS 1209-51/52	s	90×65	48	2	12	07	00	-52	10
G296.8-0.3	1156-62	s	14	9	8[a]	11	56	00	-62	18
G302.3+0.7		s	15	5.5	8[a]	12	42	55	-61	52
G309.8+0.0		s	24	17	5[a]	13	47	00	-61	50
G312.4-0.4		s	36×27	44?	5	14	09	20	-61	29
G315.4-2.3	RCW 86, MSH 14-63	s	40	49	2.5	14	39	00	-62	17
G316.3-0.0	MSH 13-57	s	25×15	24	5[a]	14	37	40	-59	47
G321.9-0.3		s	30X20	13	5[a]	15	16	45	-57	23
G326.3-1.8	MSH 15-56	C	36	145	3.7	15	49	00	-56	00
G327.4+0.4	Kes27	s	20	34	6.4	15	44	30	-53	04
G327.6+14.6	SN1006, PKS 1459-41	S	30	19	2.4	14	59	35	-41	44
G328.4+0.2	MSH 15-57	P	6	16	12	15	51	40	-53	08
G332.0+0.2		s	10	9	10	16	09	30	-50	45
G332.4-0.4	RCW 103	s	9	28	3.3	16	13	45	-50	55
G332.4+0.1	MSH 16-51, Kes 32	s	15	26	5	16	11	30	-50	35
G335.2+0.1		s	19	18	6[a]	16	24	00	-48	40
G336.7+0.5		S	13×10	6	9[a]	16	28	30	-47	13
G338.5+0.1		C?	8	28?	12[a]	16	37	30	-46	13
G348.5+0.1	CTB 37A	s	15	72	10.2	17	10	40	-38	29
G348.7+0.3	CTB 37B	s	10	26	10.2	17	10	30	-38	08
G350.0-1.8		S?	30'!	31	4[a]	17	23	40	-38	20
G357.7-0.1	MSH 17-39	C?	3×8	37	8	17	37	15	-30	56
G359.0-0.9		s	23	23	5[a]	17	43	35	-30	15

[a] estimated using $\Sigma - D$ relationship (Clark & Caswell 1976)

[b] revised from Vasisht et al. (1995)

Table 2: Summary of observations and limiting flux densities.

Source Galactic Coordinates	Observation Duration 430 MHz (hrs)	660 MHz (hrs)	1520 MHz (hrs)	S_{min} 430 MHz (mJy)	660 MHz (mJy)	1520 MHz (mJy)	best S_{min} 400 MHz (mJy)
G4.5+6.8	...	0.8	0.6, 0.4	...	0.7	0.2	1.8
G11.2-0.3	...	0.7, 0.2	1.4, 0.8, 0.6	...	1.3	0.1	1.8
G18.9-1.1	1.4	0.8	0.6	2.0	1.2	0.2	2.3
G20.2-0.2	...	0.8	1.4, 2x1.1,0.5	...	1.1	0.1	1.8
G21.5-0.9	0.8	...	2X1.1, 0.6	2.5	...	0.1	1.9
G21.8-0.6	1.4	...	...	2.3	...	...	2.6*
G23.3-0.3	1.4	...	...	2.6	...	.	3.0
G24.7+0.6	...	1.4, 0.8	2x1.1 ,0.4	...	0.8	0.1	2.1
G27.8+0.6	1.4	0.8	2X1.1	1.8	1.1	0.2	2.0
G29.7-0.3	...	0.8	1.4, 2x1.1,0.6	...	1.0	0.1	1.8
G189.1+3.0	1.4	...	0.5	1.5	...	0.4	1.7
G260.4-3.4	2x1.4	0.8	0.6, 0.5	1.5	1.3	0.3	1.7
G279.0+1.1	1.4	...	...	0.8	...	...	0.9
G290.1-0.8	...	1.2	1.4, 1.4, 0.6	3.0	0.7	0.1	2.0
G291.0-0.1	...	1.2, 0.8	1.4	...	0.6	0.1	1.6
G292.0+1.8	...	1.4, 1.2, 0.8, 0.5	1.7, 2x1.1	..	0.4	0.1	1.2
G296.1-0.5	1.4	0.8	...	0.9	0.6	...	1.0
G296.5+10.0	4×1.4	...	...	0.8	.		1.0
G296.8-0.3	..	0.8	0.6	...	0.7	0.2	1.8
G302.3+0.7	.	2X0.8	1.4, 1.2, 0.4	...	0.6	0.1	1.6
G309.8+0.0		2X0.8	0.8, 0.6, 0.6	...	1.0	0.2	2.7
G312.4-0.4	1.4	...	...	1.8	...	...	2.1
G315.4-2.3	1.4	1.2, 0.8	0.8, 0.6	1.3	0.8	0.2	1.5
G316.3-0.0	...	1.4, 0.8	1.1, 1.1,0.8	.	0.7	0.1	1.9
G321.9-0.3	1.4	0.7	...	1.4	0.9	..	1.6
G326.3-1.8	1.4	1.2, 0.8	1.1, 1.1,0.8	2.0	1.3	0.3	2.3
G327.4+0.4	...	0.8	0.8, 0.6, 0.6	...	1.3	0.3	3.5
G327.6+14.6	2.8	0.8	1.1, 1.1,0.8	0.6	0.6	0.1	0.6
G328.4+0.2	...	2x0.6	..	...	1.3	...	3.6'
G332.0+0.2	...	1.2, 0.7, 0.6	2X0.6	...	1.0	0.2	2.9
G332.4-0.4	1.4	1.2, 0.8	2.8, 2X1.1 0.8	2.5	1.1	0.1	1.5
G332.4+0.1	.	0.7	2x1.4, 2x0.6	...	1.4	0.1	2.0
G335.2+0.1	...	2.8			0.7	...	1.9'
G336.7+0.5	...	0.8	2X0.6	..	1.0	0.2	2.6
G338.5+0.1	..	...	1.4	..	...	0.1	2.1
G348.5+0.1	..		0.6	...	...	0.3	4.1
G348.7+0.3	.	0.6	0.6	...	1.5	0.2	3.1
G350.0-1.8	...	2.8	...	...	0.5	...	1.4
G357.7-0.1	...	0.8	1,4, 0.6	.	2.4	0.2	2.6
G359.0-0.9	..	1.4		...	1.4		3.8

*These values for S_{min} may be significantly underestimated because of scattering and dispersion in the interstellar medium. See § 5.5 for details.

Table 3: Previously Known Pulsars Detected

Target	Pulsar	log τ (yr)	f (MHz)	S_f (mJy)	Offset (')
G27.8+0.6	PSR B1838-04	5.66	430	2.6	20
G189.1+3.0[a]	PSR B0611+22	4.95	430	29	35
G260.4-3.4	PSR B0833-45[b]	4.05	430	5000	199
G279.0+1.1	PSR B0953-52	6.59	430	29	23
G296.1-0.5	PSR B1154-62	6.21	430	145	44
G296.8-0.3[c]	PSR B1154-62	6.21	1520	10	13
G332.0+0.2[d]	PSR B1610-50	3.87	1520	2.5	11
G359.0-0.9	PSR B1742-30	5.74	660	44[e]	27

[a] An association between these two sources has been suggested previously by Davies, Lyne & Seiradakis (1972).

[b] Vela pulsar.

[c] An association between these two sources was suggested by Large & Vaughan (1972).

[d] An association between these two sources has been discussed by Caraveo (1993) and Johnston *et al.* (1995b).

[e] Flux interpolated from Lorimer *et al.* (1995).

Table 4: Astrometric, Spin, and Radio Properties for PSR J1104-6103 and PSR J1627-4845.

	PSR J1104-6103	PSR J1627-4845
Right Ascension, α (J2000)	$11^h\,04^m\,17.262^s \pm 0.011^s$	$16^h\,27^m\,10.34^s \pm 0.12^s$
Declination, δ (J2000)	- 61°03'03.88" ± 0.08"	- 48°45'08" ± 3"
Right Ascension, α (B1950)	$11^h\,02^m\,12.963^s \pm 0.011^s$	$16^h\,23^m\,26.90^s \pm 0.12^s$
Declination, δ (B1950)	- 60°46'51.93" ± 0.08"	- 48°38'25" ± 3"
Period, P (s)	0.2809053015394(18)	0.61233065088(9)
Period Derivative, $\dot{P}$	$1.96673(20) \times 10^{-15}$	$3.641(10) \times 10^{-15}$
Epoch of Period (MJD)	49177.00	49200.00
Dispersion Measure, DM (pc cm^{-3})	78.506(15)	558(4)
Surface Magnetic Field, B (G)	7.5×10^{11}	1.5×10^{12}
Characteristic Age, τ (yr)	2.3×10^{6}	2.7x1($
Spin-down Luminosity, $\dot{E}$ (erg s^{-1})	3.5×10^{33}	6.3×10^{32}
Flux density at 1520 MHz (mJy)	0.4	0.2
Half-power Pulse Width at 1520 MHz (ms)	10(1)	41(2)
Flux density at 430 MHz (mJy)	5.0	...
Half-power Pulse Width at 430 MHz (ms)	9(1)	...
Spectral Index	-2.0	...
R.M.S. timing residual (ms)	0.57	9.00

Fig.),- Average pulse profiles at 430 and1520 MHz for PSR J1 104—-61 03. In each case, the whole period is displayed and the instrumental smoothing is smaller than the time resolution which is 1/128 of the period.

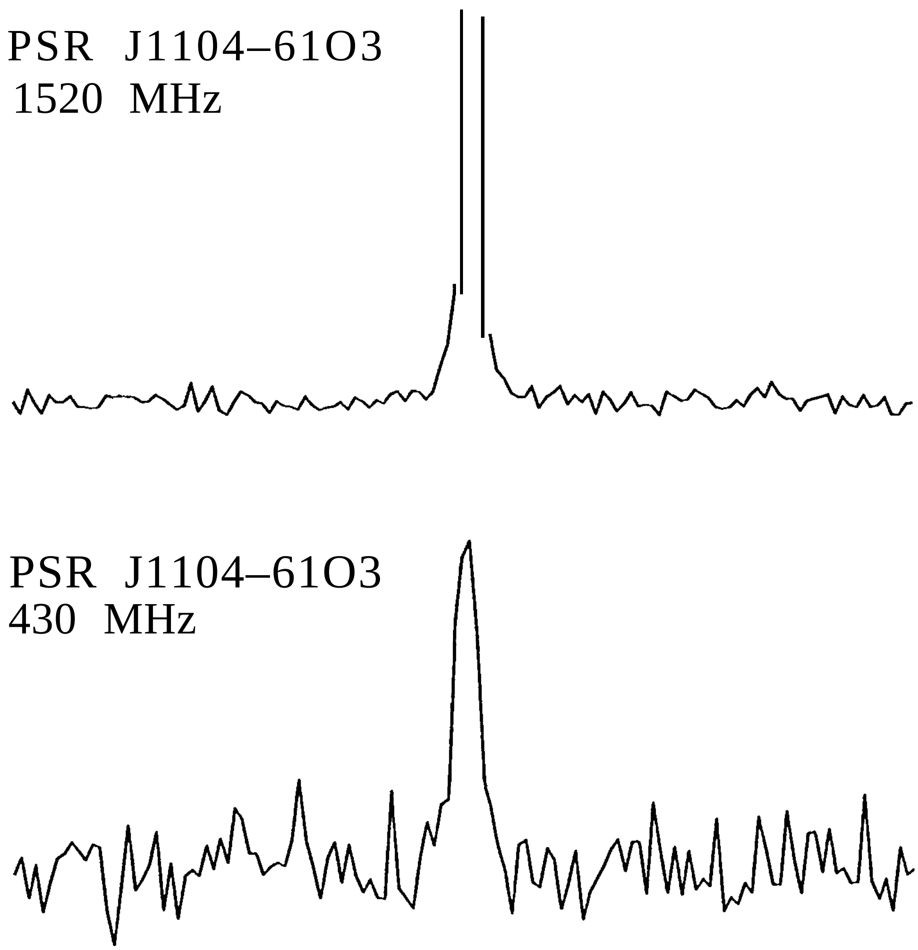

Fig. 2.- Average pulse profiles at 660 and 1520 MHz for PSR J1627-4845. In each case, the whole period is displayed and the instrumental smoothing is smaller than the time resolution which is 1/128 of the period. The 660 MHz profile is from the discovery observation.

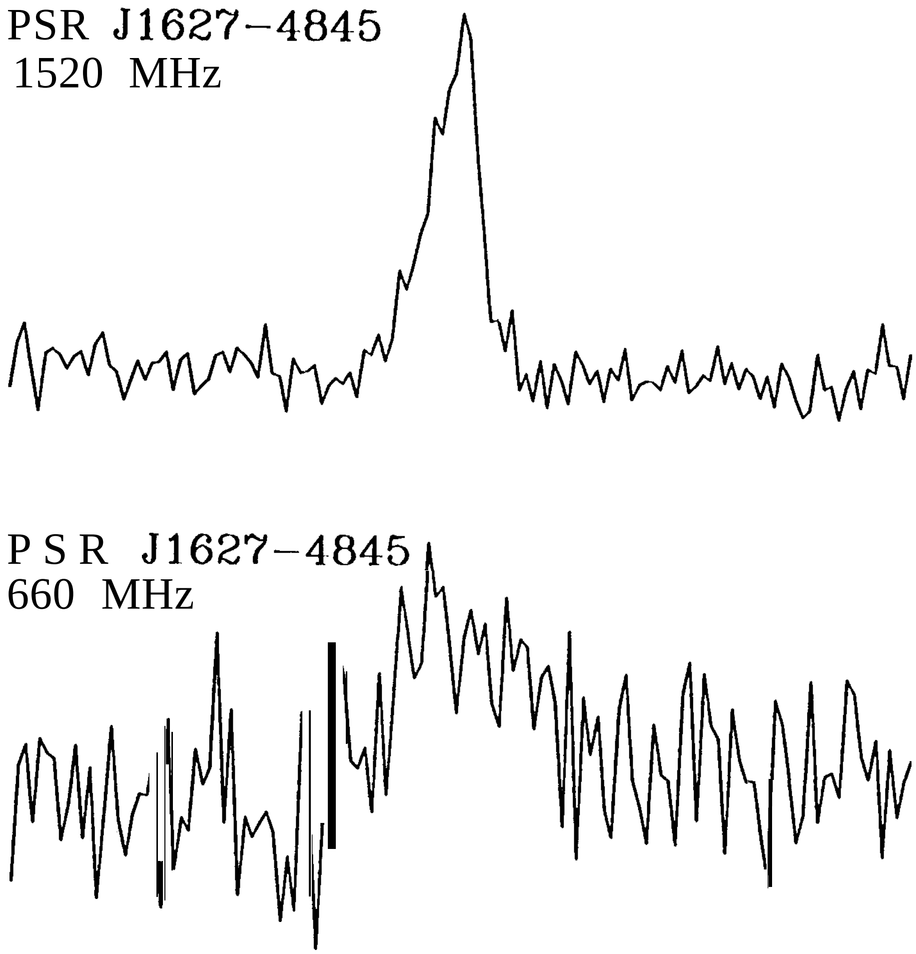

Fig. 3.- Comparison of this survey's sensitivity with the luminosity distribution of the known pulsar population. The striped area shows the 400 MHz luminosities of the pulsars in the Taylor, Manchester & Lyne (1 993) catalog, the crossed region the 400 MHz luminosities of the 21 known pulsars having characteristic ages less than 10^5 yr, and the vertical line shows the mean upper luminosity limit for pulsars in the target remnants of this survey.

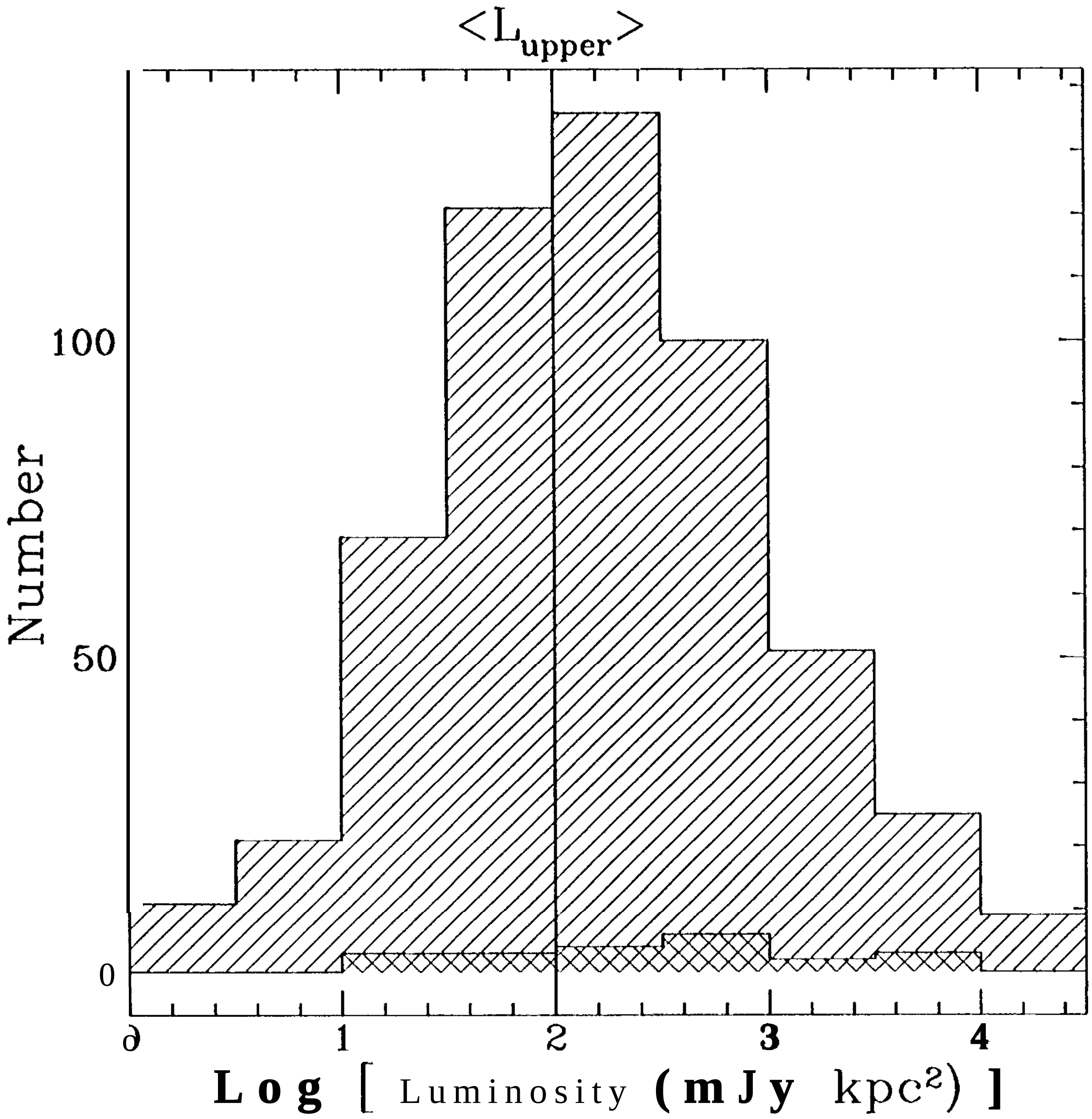

Fig. 4.- Image of G335.2+0.1 at 843 MHz, after Whiteoak & Green (1996). The position of PSR J1627−4845 is indicated by a cross, which is much larger than the uncertainty.